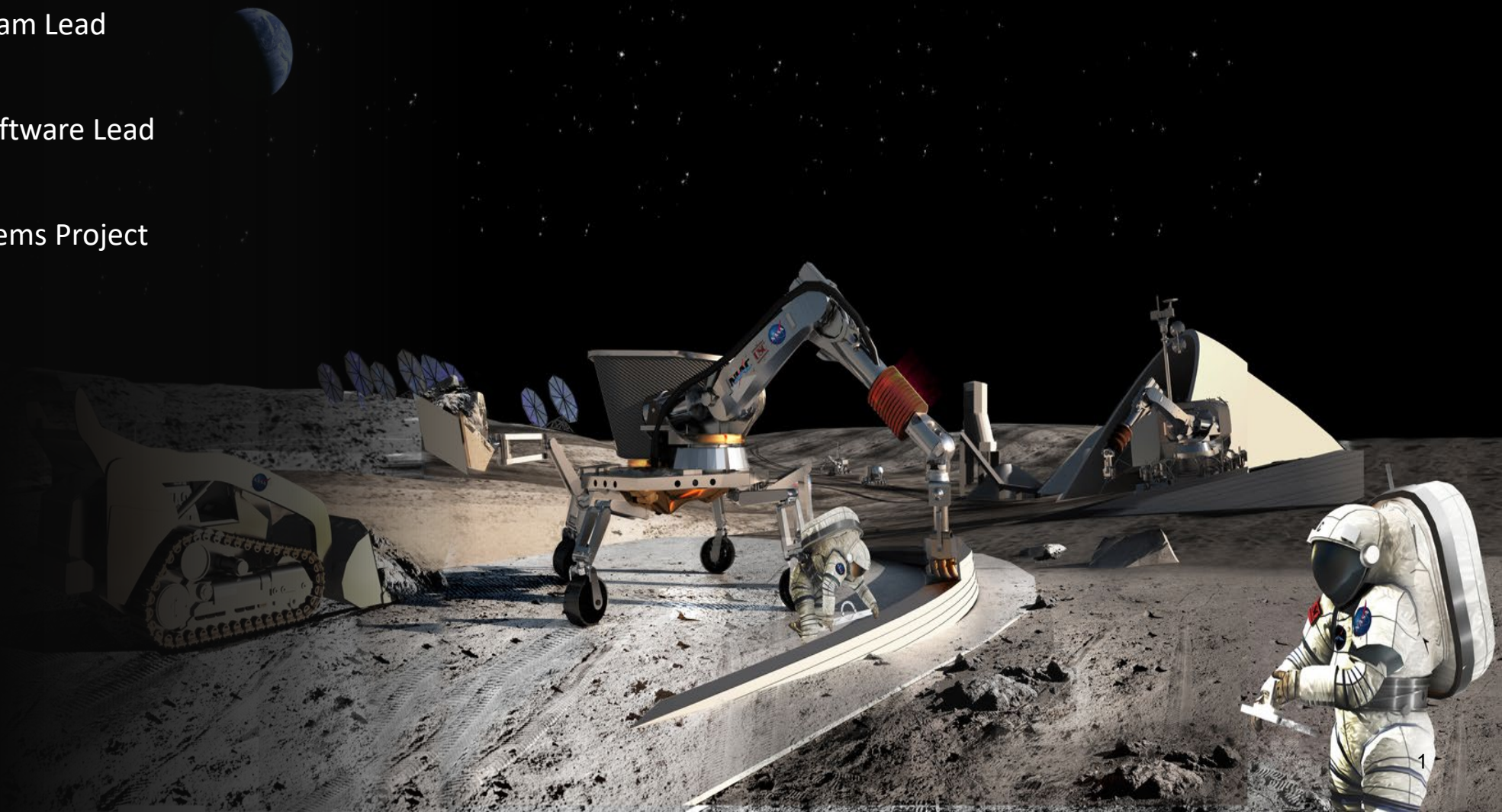
Power Multi-Microgrid Transmission Control for a Lunar Surface Power System

Marc Carbone
Autonomous Power Control Team Lead

Matt Muscatello
Autonomous Power Control Software Lead

Jeffrey Csank
Advanced Modular Power Systems Project Manager

NASA Glenn Research Center
Cleveland, OH 44135



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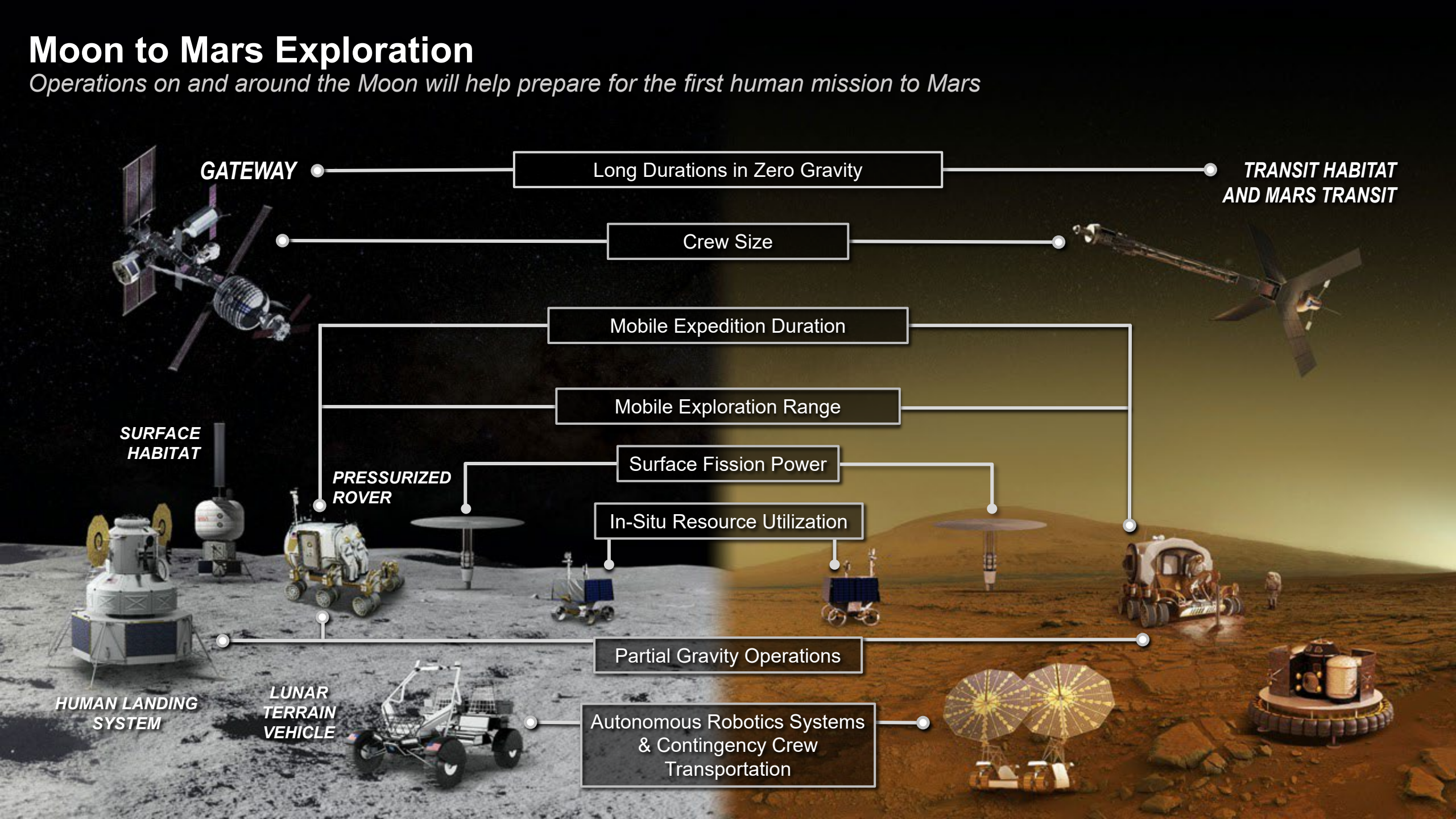
Moon to Mars Exploration

Operations on and around the Moon will help prepare for the first human mission to Mars

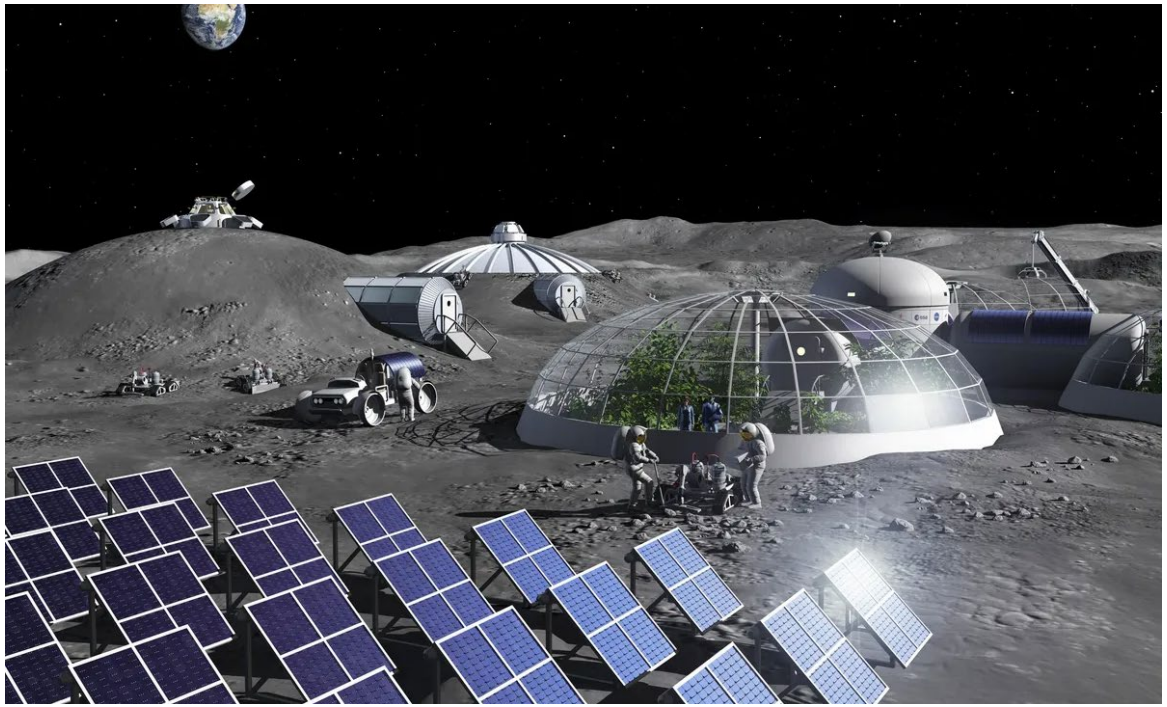


Autonomous Power Controller (APC)

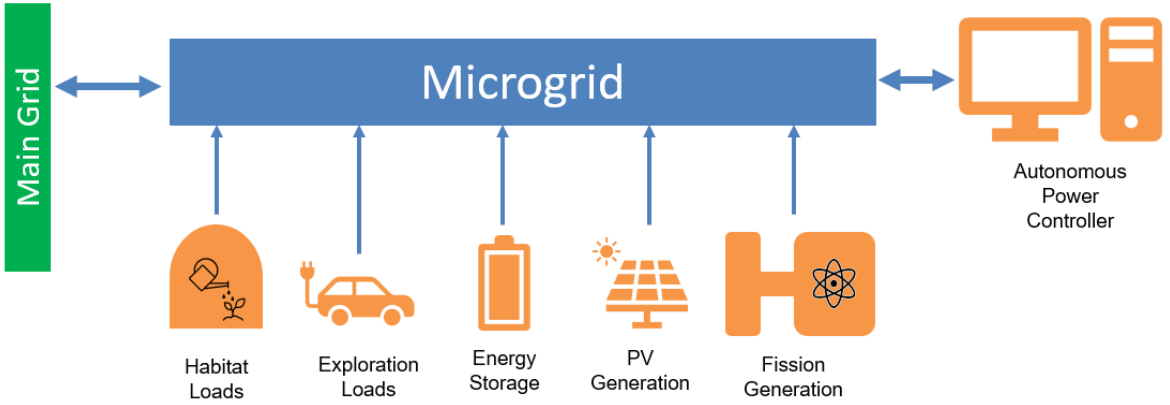
Why is this Project/Activity Important?

Future space missions and systems require power systems that can:

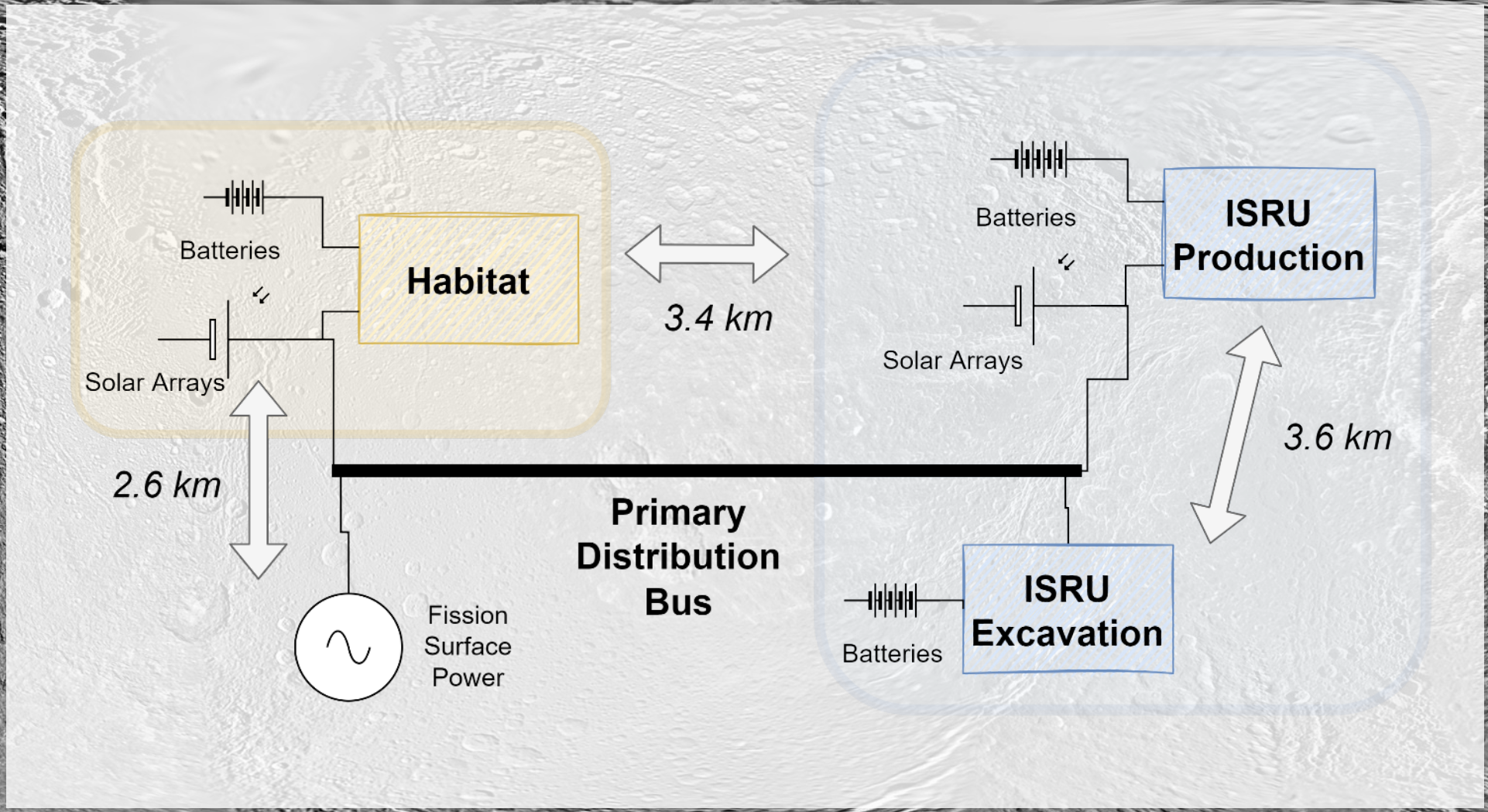
- Increase the reliability, resilience and autonomy of a space-based electric power system (EPS)
- Develop effective control strategies to achieve system-level autonomy and interoperability
- Deliver highly reliable power to various systems to meet the unique power demands of loads under the extreme lunar and Martian environments
- Grow and reconfigure as operations grow and adapt
- Minimize maintenance and downtime (advanced fault detection, automatic reconfiguration, and provide maintenance support)



- **Power System Operation**
  - The lunar grid will require extremely reliable and robust control to maintain operation
  - Advanced controls needed to achieve these goals

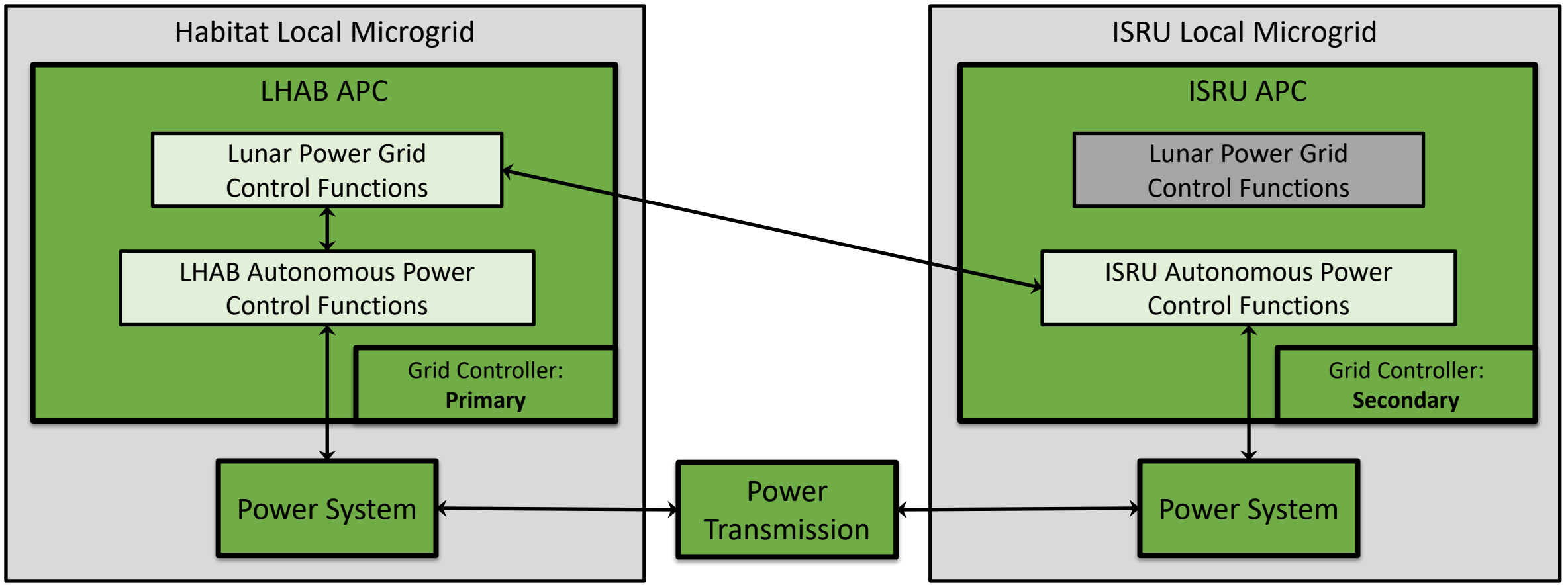


Proposed Lunar Microgrid Architecture



Note this is not the actual lunar surface or mapping

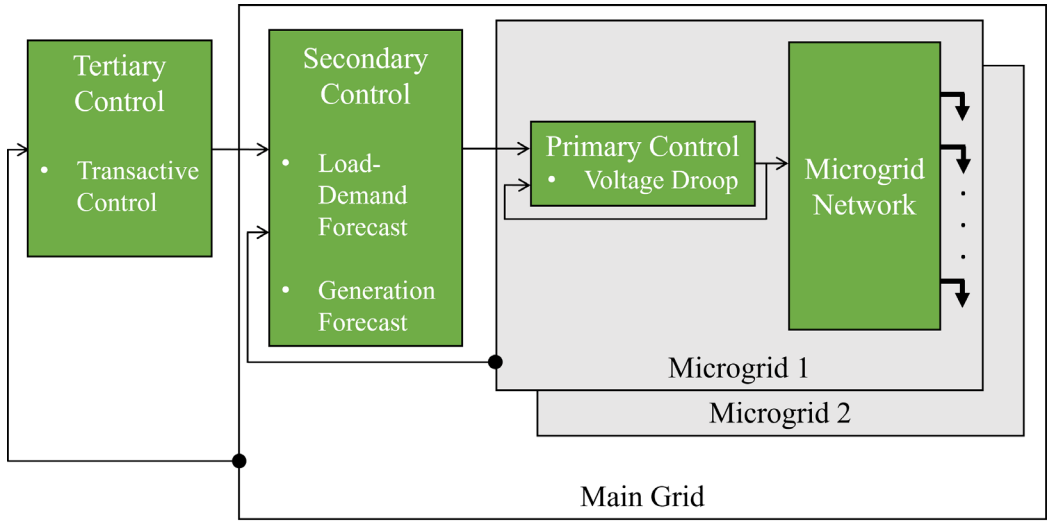
Power Sharing Architecture



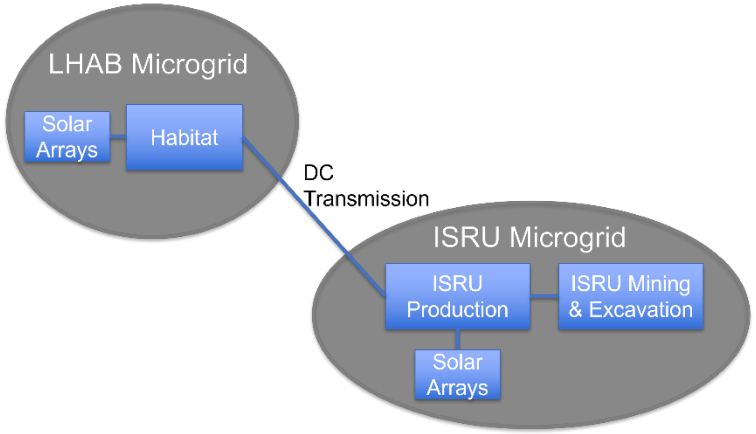
- One Local Microgrid Controller is the leader
  - Responsible for executing the Lunar Power Grid Controller Functions
- All other Local Microgrid Controllers are followers
  - Lunar Power Grid Controller Functions are disabled

Hierarchical Microgrid Control

- **Primary (Device Controller)**
  - Operates on a fast time scale (micro-seconds)
  - Responsible for output power control and voltage regulation
  - Handles power sharing (balancing) via droop control
  - Detects faults using physics-based rules
  - Isolates faults using automatic protection
- **Secondary (Microgrid Controller)**
  - Operates on a medium time-scale (seconds)
  - Responsible for the reliable, secure, and economical operation of a microgrid (in connected or islanded mode)
  - Determines optimal set-points from deviations in the primary controller
  - Identifies low-magnitude faults and sensor failures
  - Determines appropriate corrective actions against faults/disturbances
- **Tertiary (Grid Controller)**
  - Operates on a long time-scale (minutes)
  - Responsible for coordinating multiple microgrid interactions
  - Communicates needs from a local microgrid (e.g. voltage support)
  - Sets long term set-points
  - Determines loss minimization for the entire grid



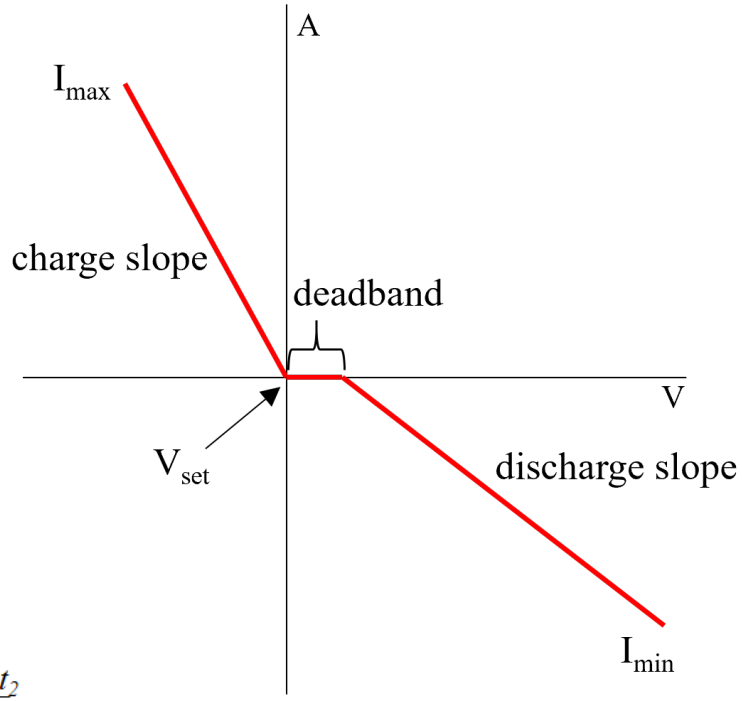
Hierarchical microgrid control architecture

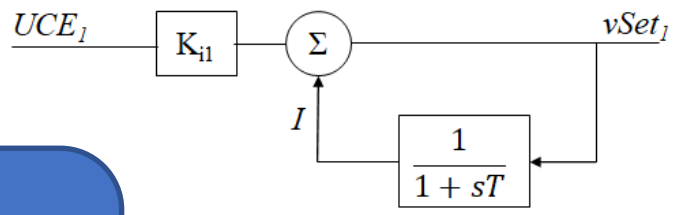


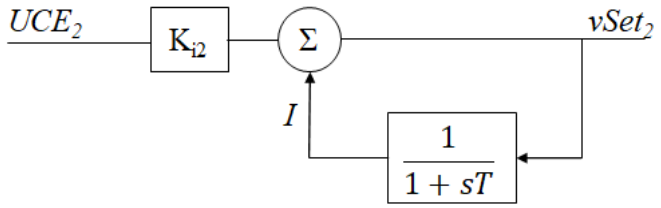
One Line Diagram of the power system architecture

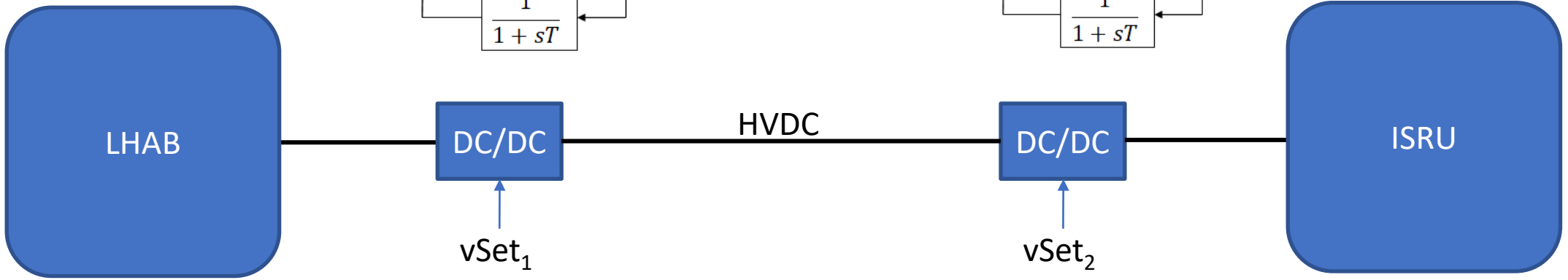
Primary Controller

- **Low-level control for DDCU implementation**
  - 5-10Hz update rate
  - Operates in voltage droop mode
  - Determines output based on measured grid voltage
  - APC sends voltage setpoint to control output
  - Regulates voltage setpoint to achieve constant power transfer
  - Uses feedback to determine voltage setpoint



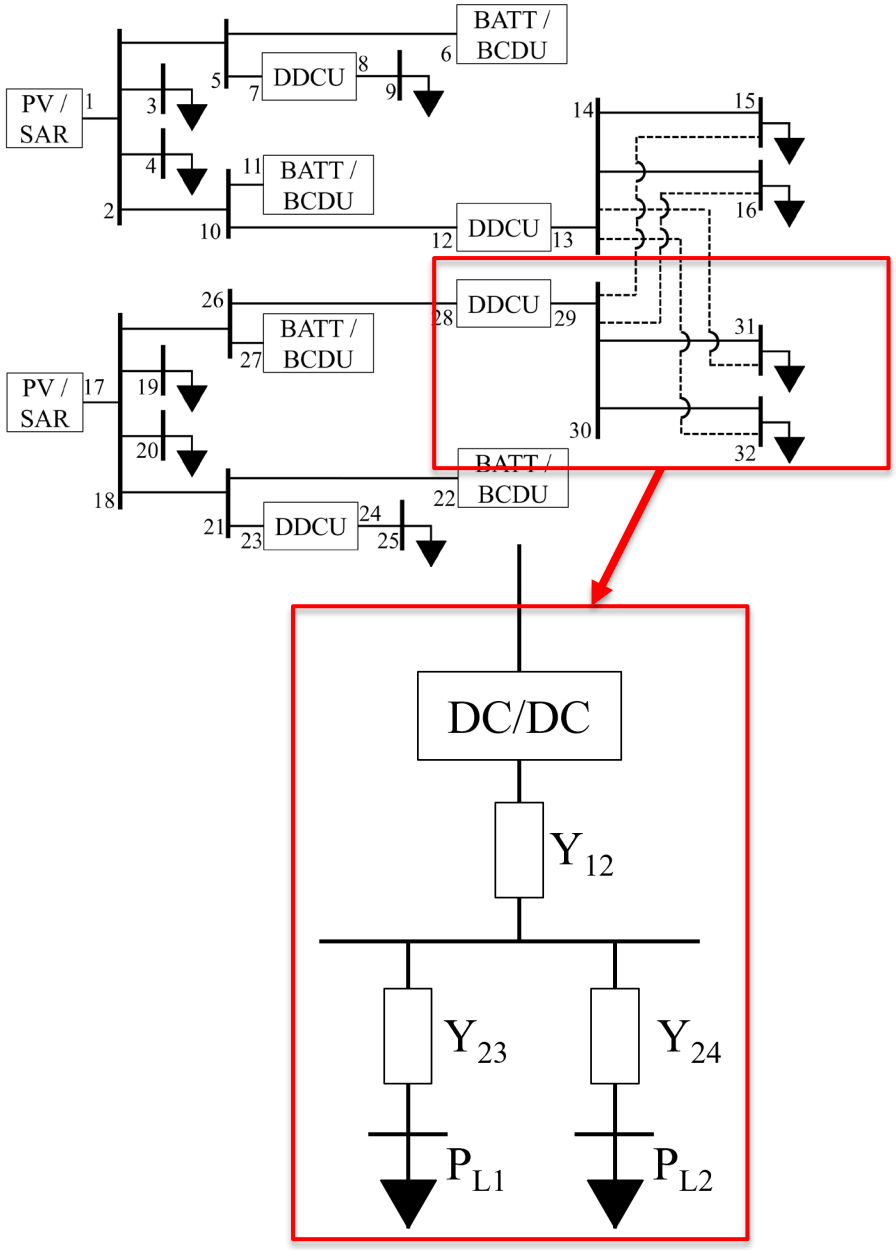






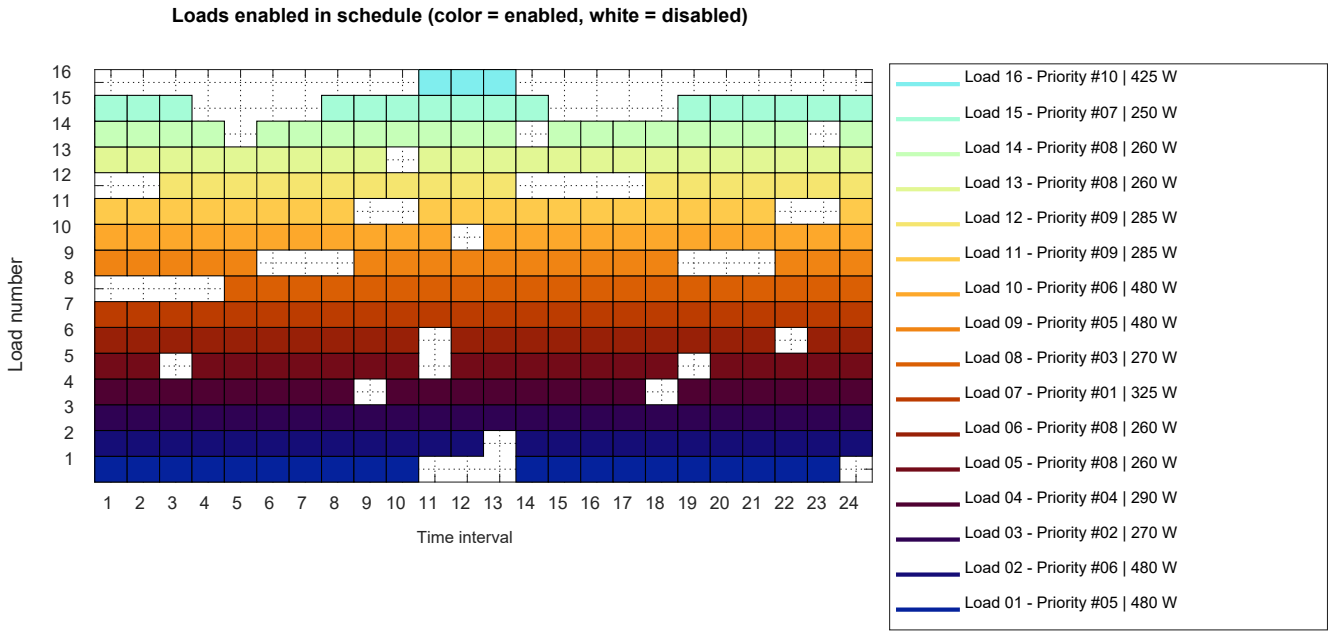
Secondary Controller

- **Power Generation Forecast**
  - Power Flow
    - Solves for the power system bus voltages and powers using Newton-Raphson solver
    - Solves entire microgrid based on power electronics “sub-islands”
    - Inspired by LEP’s SPACE / ECAPS code
    - Increases load in the MG until power system constraints are violated
  - Determines the max load that can be supported from the solar arrays (insolation) or batteries (eclipse)
  - Calculates insolation and eclipse values
  - Only updates when the power system changes (e.g. faults, reconfiguration, etc.)



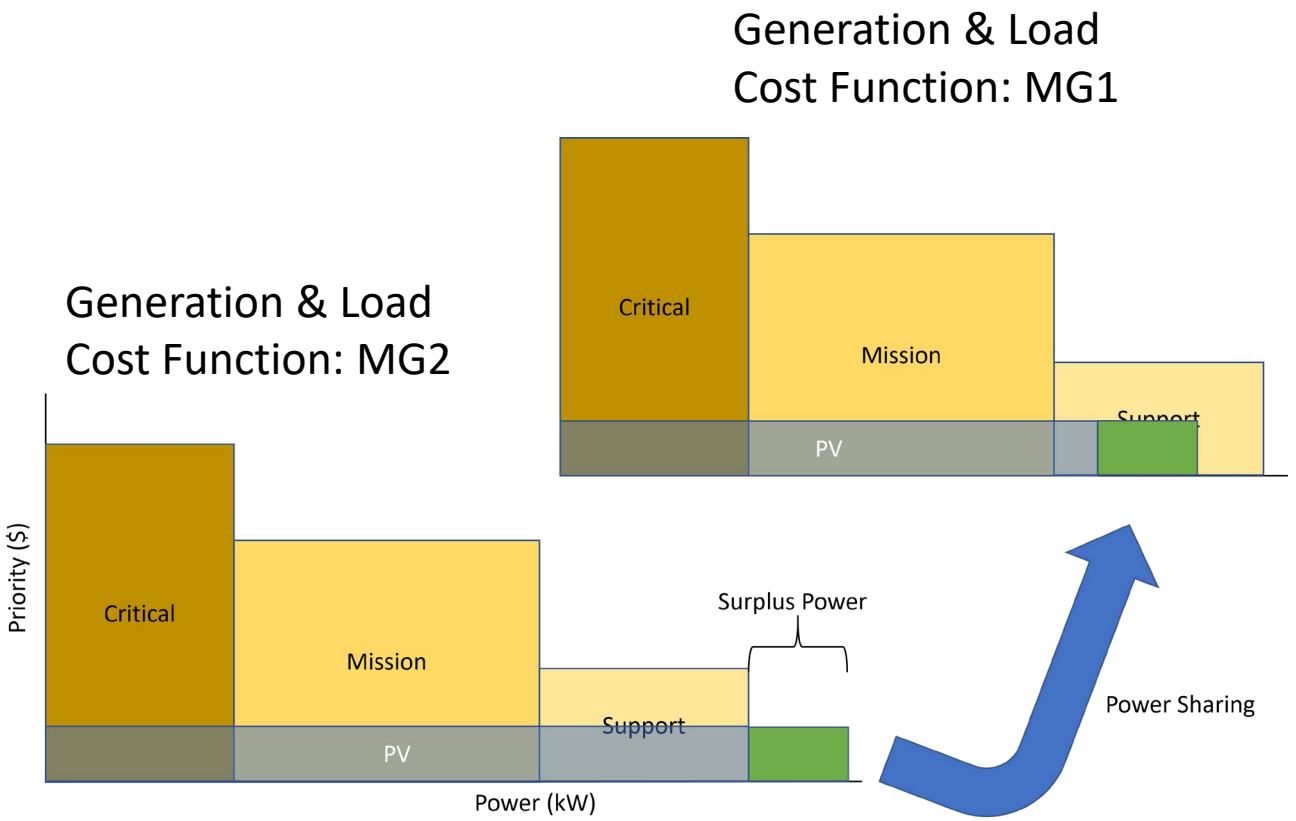
Secondary Controller

- **Load forecast**
  - Load schedule sent from controller operator for future time window
  - Each load is given a unique priority and classification
    1. **Critical:** Load required to maintain lunar base (e.g., life support systems)
    2. **Mission:** Load required to support mission objective but not necessary lunar base operations (e.g., scientific experiments)
    3. **Support:** Loads not required to maintain the lunar base or mission objectives



Tertiary Controller

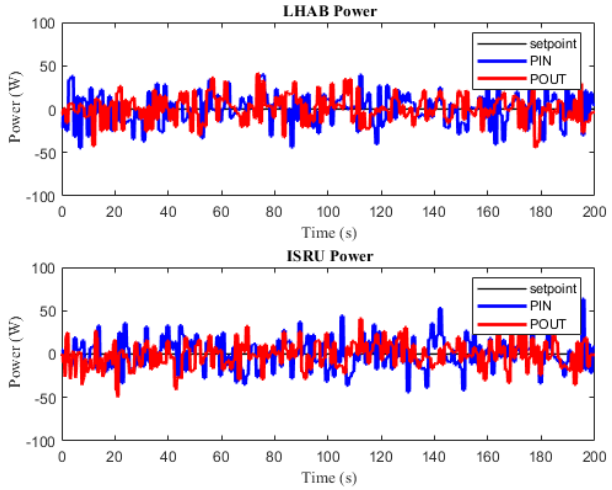
- **Grid-Level Controller**
  - Transactive control approach
  - Determines the surplus/deficit of each MG
  - Computes power sharing capability
    - Includes a margin of error to account for losses in power electronics and HVDC transmission line
  - Allocates power in order of priority
  - Returns power setpoint to primary controllers

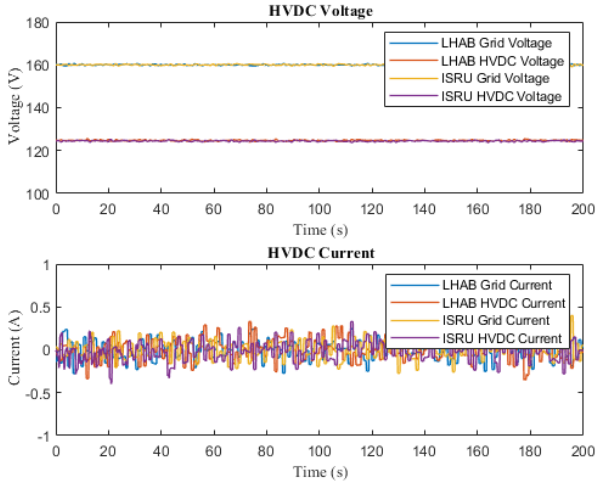


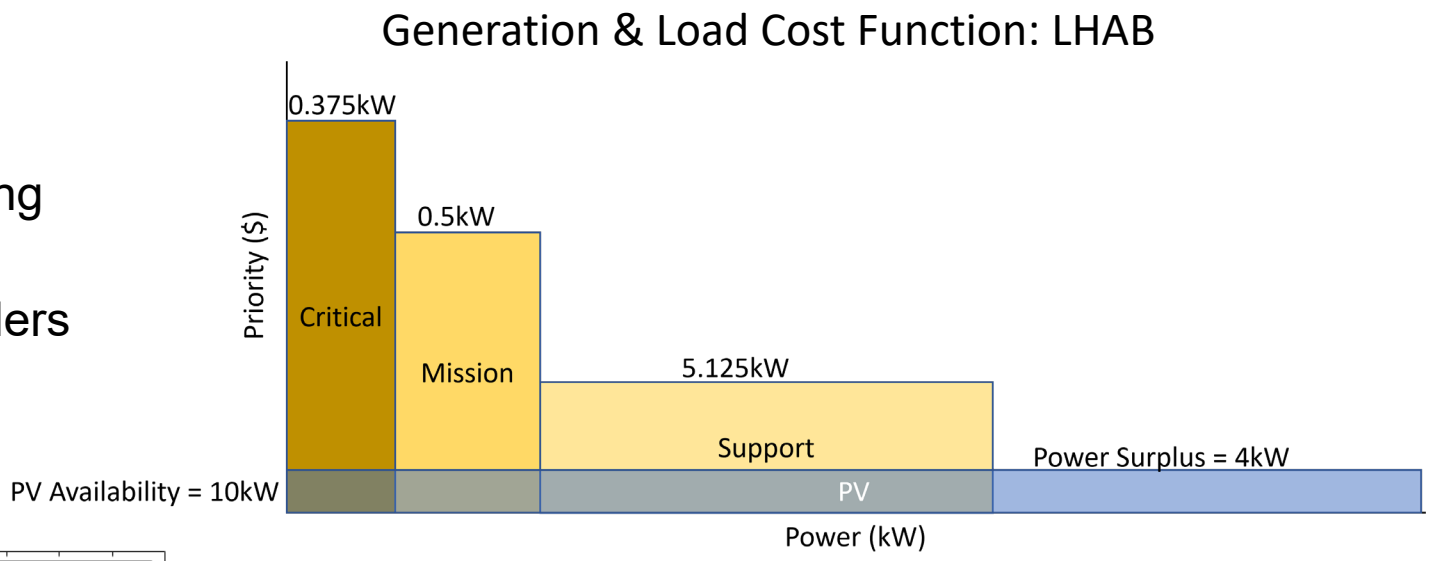
Use-Cases

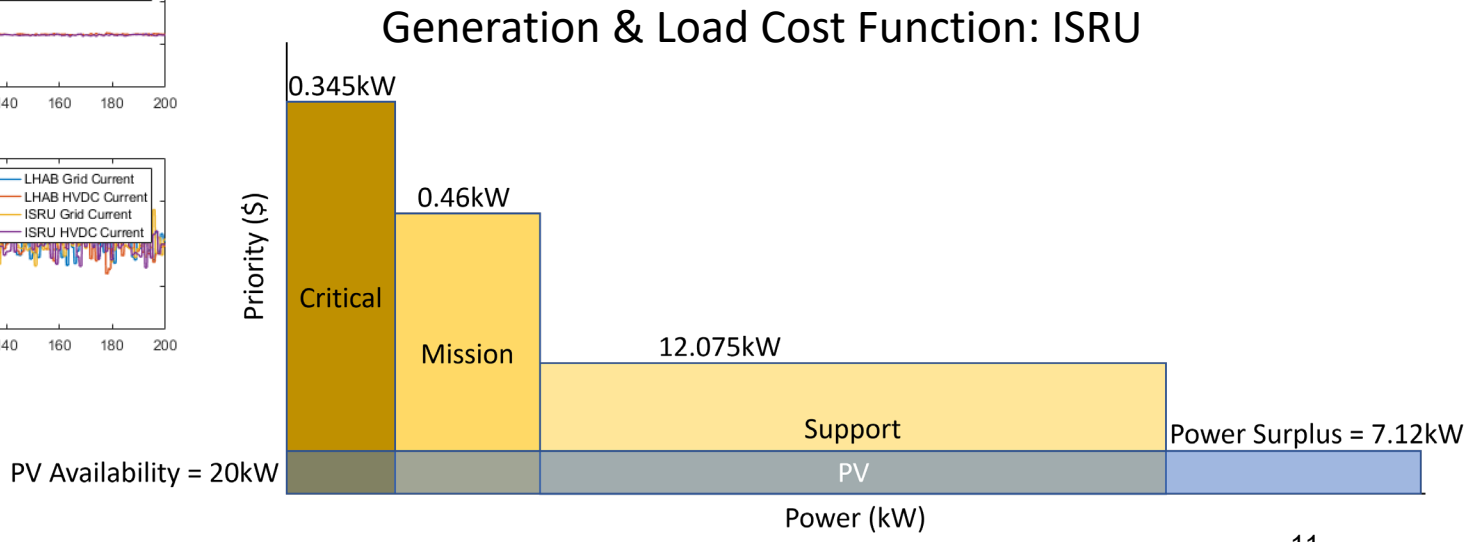
1. Islanded Mode

1. Each microgrid has a power surplus
2. Tertiary controller determines power sharing is not needed
3. 0kw setpoint is sent to the primary controllers





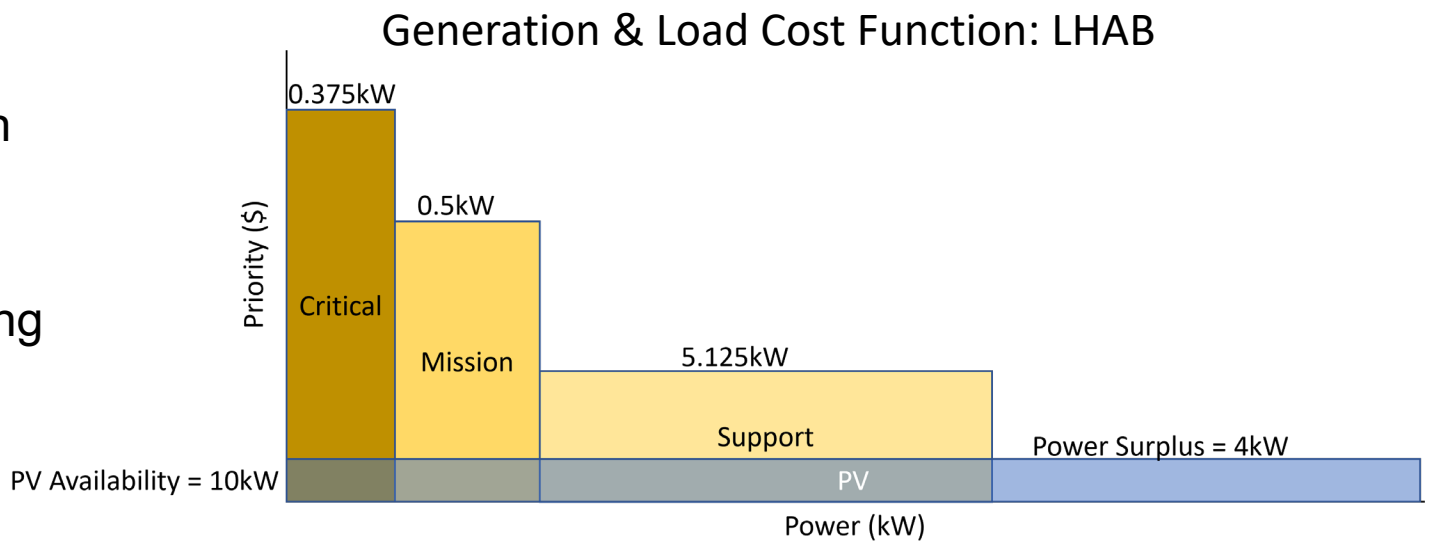


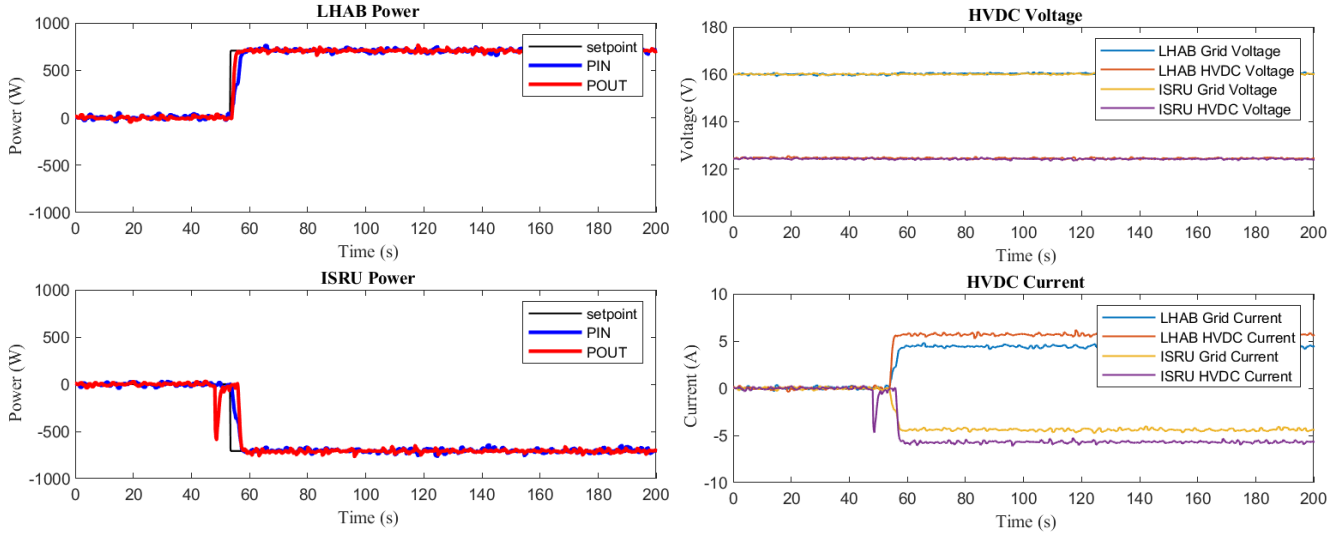


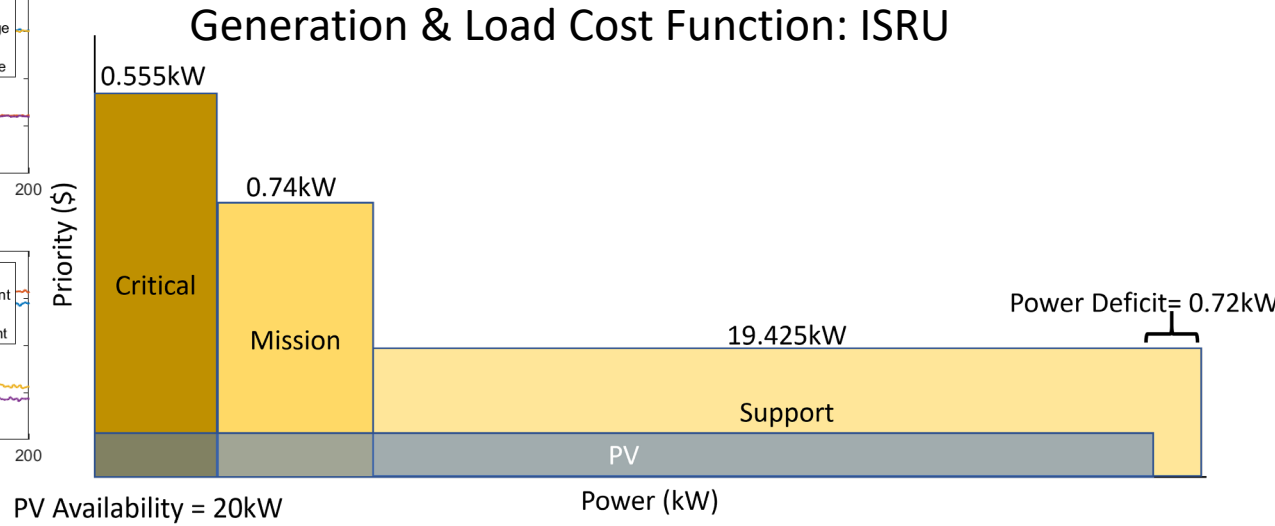
Use-Cases

2. Normal Power Sharing Mode

1. An increased load schedule is proposed in ISRU
2. A power deficit is computed in ISRU
3. Tertiary controller determines power sharing can be used to support the extra load
4. 0.80kw setpoint is sent to the primary controllers



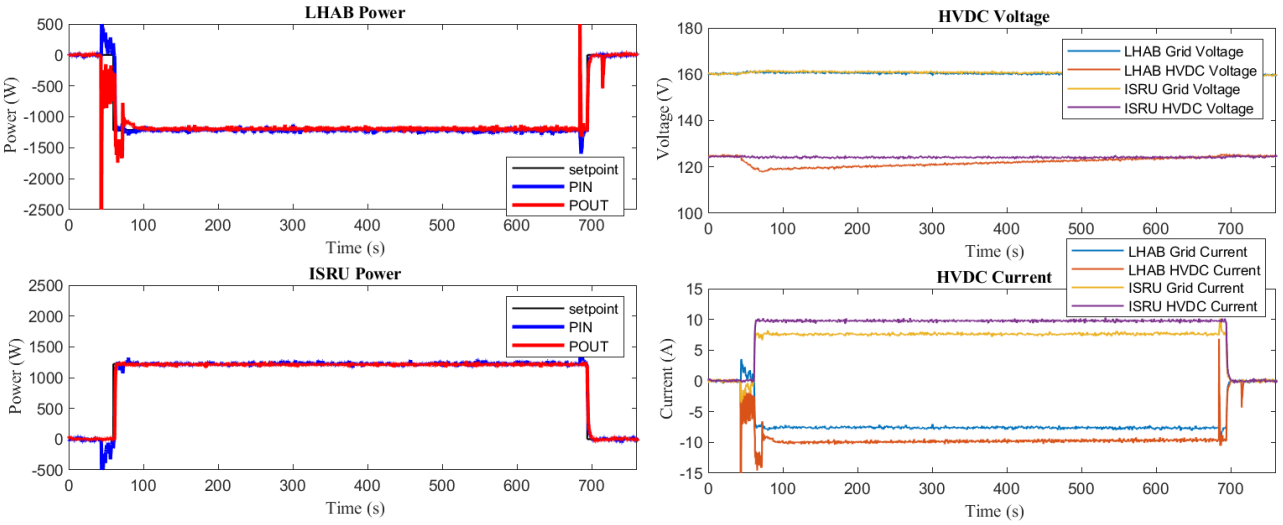


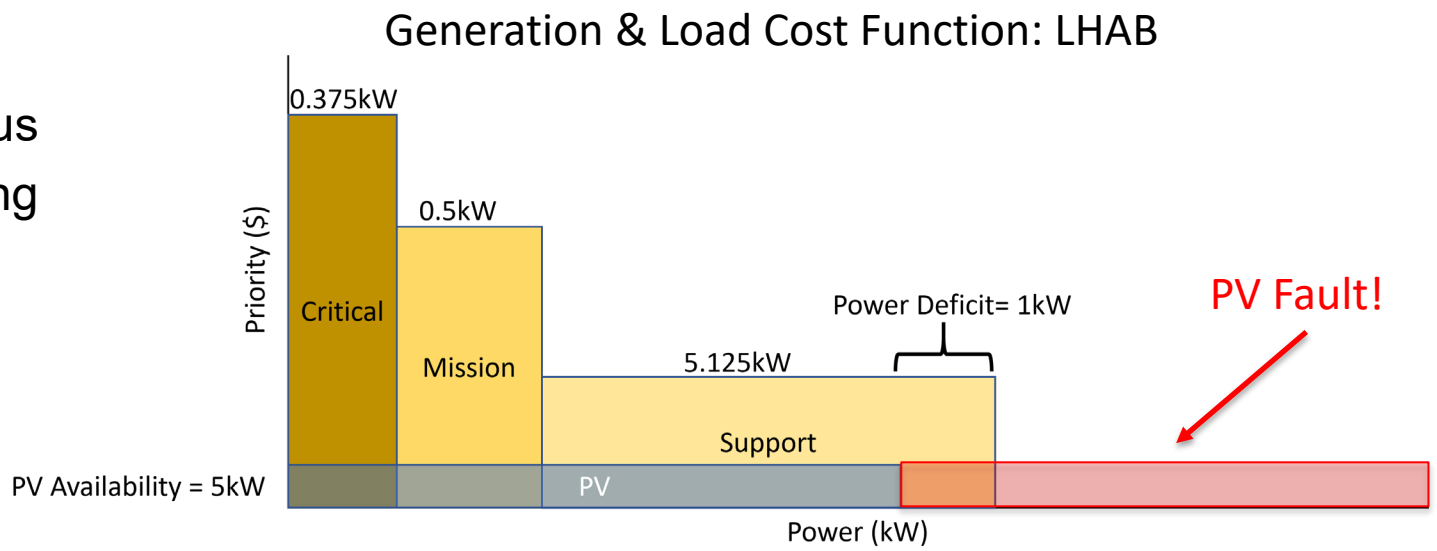


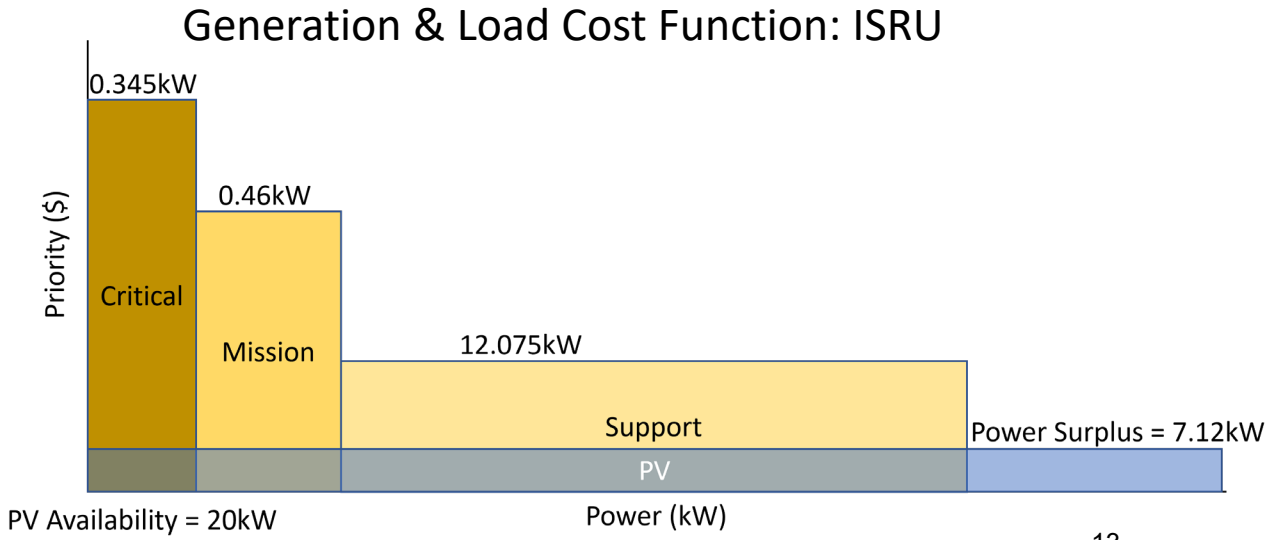
Use-Cases

3. Faulted Mode (Insolation)

1. Each microgrid begins with a power surplus
2. A solar array fault occurs in LHAB, resulting in a reconfiguration
3. Power flow is recalculated and sent to the grid controller
4. The tertiary controller determines that the remaining 1kW can be supported from ISRU



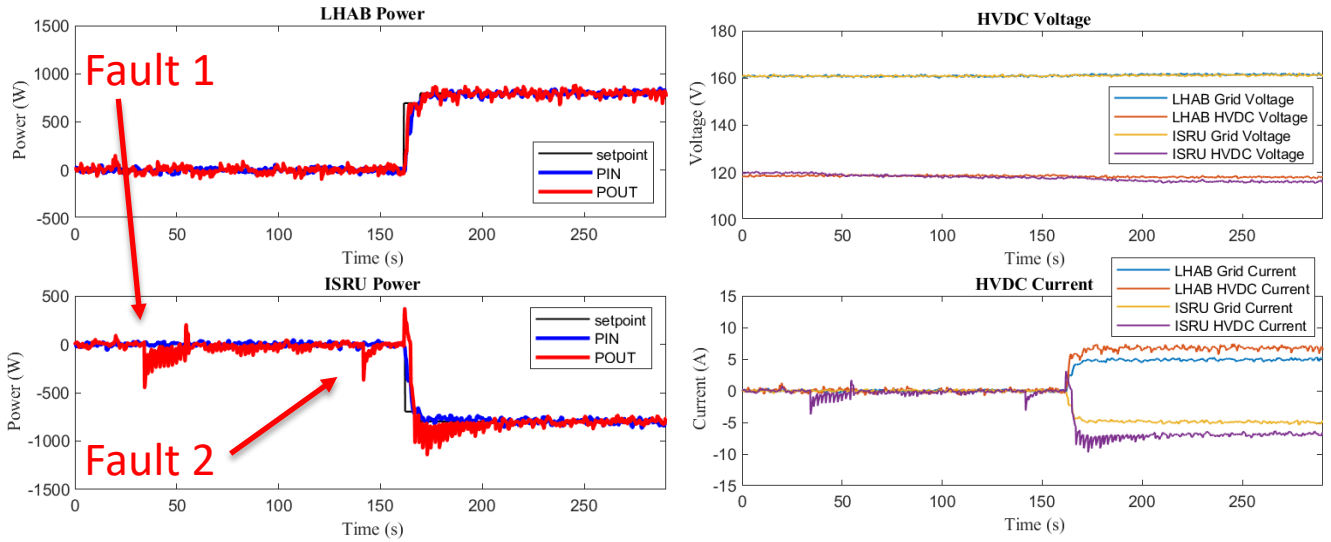


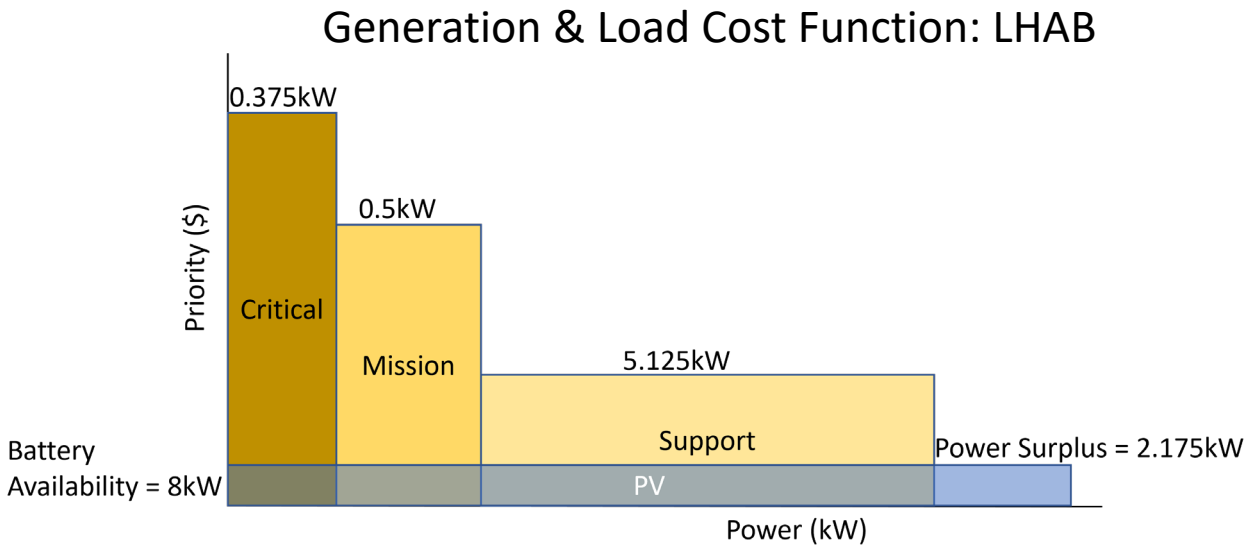


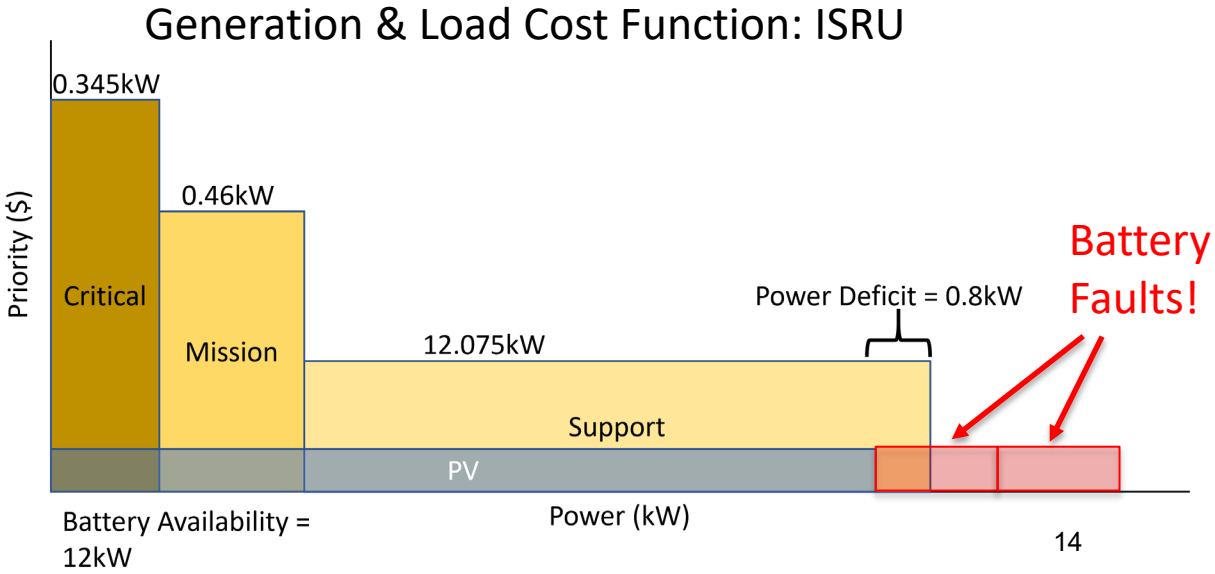
Use-Cases

4. Faulted Mode (Eclipse)

1. Each microgrid begins with a power surplus based on eclipse generation capability
2. A battery fault occurs in ISRU, but a power surplus remains
3. A second battery fault occurs in ISRU, resulting in a power deficit
4. The tertiary controller determines that the remaining 0.8kW can be supported from LHAB







Conclusions

- **Hierarchical power sharing controller**
  - Primary Layer: Sets DDCU voltage setpoint to achieve desired power flow
  - Secondary Layer: Calculates the generation and load forecast for each microgrid
  - Tertiary Layer: Determines power flow between the microgrids
- **Structure could be adapted to support AC transmission**
  - Update primary controller to achieve desired power flow
- **Possible additional work for advanced cases**
  - Expand control to handle 3 or more microgrids
  - Decision making on load shedding when generation < load
  - Cost function analysis based on battery state-of-charge
  - Optimal Power Flow (OPF) to determine “best” economic dispatch

Thank you